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Magnetization precession and domain-wall structure in cobalt-ruthenium-cobalt trilayers

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The magnetization dynamics of Co(5 nm)/Ru/Co(5 nm) trilayers with Ru thicknesses from 0.3–0.6 nm is experimentally and theoretically investigated. The coupling between the Co layers is antiferromagnetic (AFM) and yields a stable AFM domain structure with frozen domain walls. Comparing high-resolution magnetic force microscopy (MFM) and pump-probe measurements, we analyze the behavior of the films for different field-strength regimes. For moderate magnetic fields, pump-probe measurements provide dynamic characterization of the coupled precessional modes in the GHz range. The dynamics at small fields is realized by the pinning of AFM domain walls at inhomogeneities. The MFM images yield a domain-wall width that varies from about 150–60 nm. This behavior is explained in terms of a micromagnetic local-anisotropy model.
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Since the original discovery of antiferromagnetic coupling in Fe/Cr/Fe layered structures,[1] thin films composed of magnetic layers separated by a nonmagnetic spacer have received considerable attention due to their applications in spin valve devices.[2] Compared to the oscillatory behavior of the interlayer exchange coupling between the ferromagnetic (FM) and AFM,[3,4] the spin structure and dynamics of the films have attracted much less attention. The dynamics of the trilayers in the GHz range determines the high-speed response and is of fundamental importance for the enhancement of the areal density and data processing speed in magnetic storage devices.[5] The magnetic domain and domain wall configurations of trilayers with AFM coupling display a number of interesting features.[6,7] For example, domain walls in Co/Ru/Co trilayers with Co layers of equal thickness are frozen, and an applied magnetic field does not change the domain-wall position but leads to a narrowing of the domain walls.[8] Such freezing effects are common in ordinary antiferromagnets,[9] but have not been observed before in trilayers. This paper deals with the ultrathin Co/Ru/Co trilayers. We previously found that an interlayer Ru thickness range of 0.3–0.6 nm results in stable AFM coupling between two 5 nm Co layers.[8] We use pump-probe techniques to analyze the magnetization precession, evaluate the interlayer exchange coupling with the help of a Landau-Lifshitz-Gilbert (LLG) based model,[10] and investigate the domain-wall narrowing as a function of magnetic field.

Co/Ru/Co trilayer thin films were prepared by dc-magnetron sputtering on Si (100) substrates at deposition rates of 0.486 Å/s for Co and 0.276 Å/s for Ru, in a 4 mTorr argon pressure. The base pressure was approximately 1×10^{-7} Torr. The thicknesses of the top and bottom Co layers were fixed at 5 nm, while the thickness of the Ru interlayer was varied from 0.3–0.6 nm. The magnetization precession measurements were performed using a 150 femtosecond laser (50 nJ/pulse, 800 nm) in a pump-probe experiment with direct optical excitation.[11] Room temperature high-resolution MFM imaging in the presence of an in-plane magnetic field was carried out using a DI Dimension 3100 SPM in tapping/lift mode with a lift height of 15 nm.

In our Co/Ru/Co structures, the ferromagnetic layers are strongly antiparallel coupled when the Ru interlayer thickness is varied from 0.3–0.6 nm. All samples show two types of coupled modes, classified as acoustic mode (AM) and optic mode (OM) depending on whether the two film magnetizations precess in phase or out of phase, respectively. For antiparallel configuration, the two magnetizations precess in opposite directions, and hence their relative phase changes continuously. Figure 1(a) shows the pump-induced changes of Kerr rotation (ΔKerr) as a function of the delay time for the 5 nm Co/0.4 nm Ru/5 nm Co sample with various strengths of applied field at 45° relative to the sample normal. The clearly visible beats in the precession indicate the presence of two modes. Figure 1(b) shows the corresponding Fourier transformations of Fig. 1(a). The two frequency branches start merging with increasing magnetic field until only one broad peak is observed at H = 6 kOe. The peaks then separate for larger fields. This behavior is illustrated in Fig. 2 which shows the precessional frequency (solid square) as a function of applied field.

To interpret these results, we use a two-layer LLG based model. The energy per unit area of the trilayer system can be written as:

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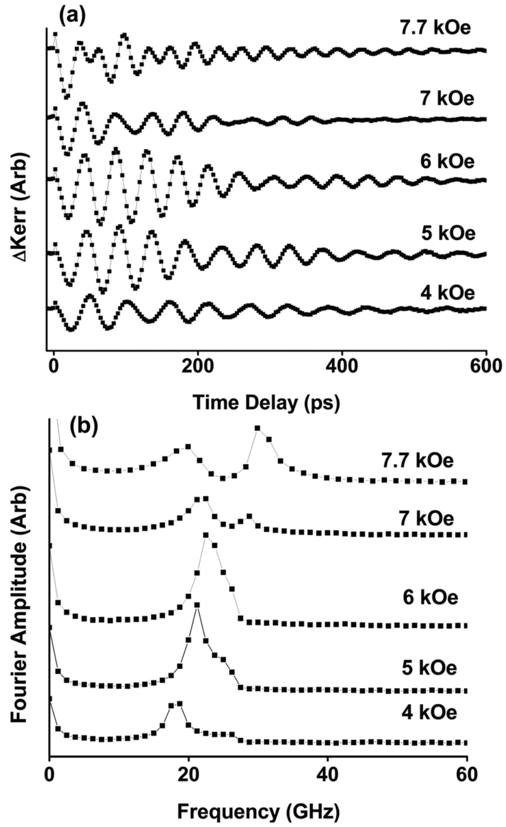

FIG. 1. (a) Typical pump-probe signals as a function of time for the sample 5 nm Co/0.4 nm Ru/5 nm Co with various strengths of applied field at 45° to the sample normal and (b) the corresponding Fourier transforms.

$$E = -t_1\vec{M}_1 \cdot \vec{H} + 2\pi t_1 \vec{M}_1^2 \cos^2\theta_1 - t_2\vec{M}_2 \cdot \vec{H} + 2\pi t_2 \vec{M}_2^2 \cos^2\theta_2 - J\frac{\vec{M}_1 \cdot \vec{M}_2}{M_1 M_2}. \quad (1)$$

Here, $t_{1,2}$ is the thickness of each Co layer, $\vec{M}_{1,2}$ is the magnetization of each Co layer and $\theta_{1,2}$ is the angle of $\vec{M}_{1,2}$ with respect to the sample normal. First, the energy is minimized to find the equilibrium orientations. The magnetization of each Co layer was assumed to be uniform and measured to be 1225 kA/m. These values were used as inputs in the model. We adjusted interlayer coupling constant J and solved the LLG equations to obtain frequencies similar to the experimental frequencies. The solid lines in Fig. 2 are the simulation curves obtained from this model with $J = -2.1$ mJ/m^2. The present model provides a good semi-quantitative description of field-dependence precession for our trilayers. Note that the low-frequency branch does not extrapolate to zero frequency at zero field as predicted by the calculations, and the width of the bump in the low-frequency branch is greater than predicted. The differences may be due to structural inhomogeneities. Nevertheless, the value of $J = -2.1$ mJ/m^2 here is in reasonable agreement with the value of $J = -2.6$ mJ/m^2 found in our previous static results,[8] indicating that the dynamic simulation is consistent with the static simulation. The other three AFM coupled samples ($t_{Ru} = 0.3$, 0.5, and 0.6 nm) show similar behaviors as the $t_{Ru} = 0.4$ nm sample, but with different values of J. The estimated $-J$ (J is negative) as a function of the Ru

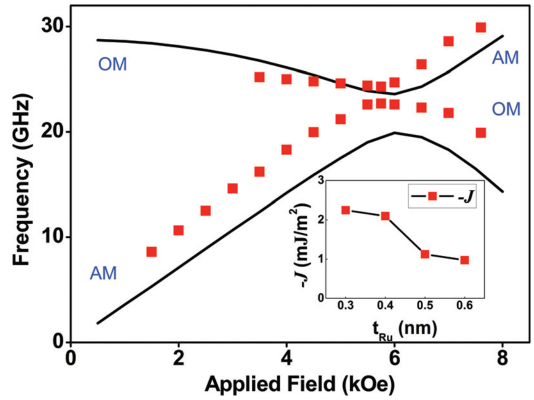

FIG. 2. (Color online) Precessional frequencies as a function of the applied magnetic field at 45° for the sample 5 nm Co/0.4 nm Ru/5 nm Co. The solid curves are the simulation from a LLG based model with $J = -2.1$ mJ/m^2. (Inset) The estimated exchange coupling J obtained from LLG based model as a function of the interlayer Ru thickness.

thickness is shown in the inset of Fig. 2. With the increasing thickness of Ru, J monotonically decreases, showing that the interlayer exchange coupling is getting weaker.

Two Co layers are AFM coupled domain by domain with the top domains antiparallel to the bottom domains, leading to zero net magnetization in the interior of the domains and so only the domain walls are observed. A high resolution scan of the domain-wall structures was performed in the 5 nm Co/0.4 nm Ru/5 nm Co sample as shown in Fig. 3. Although, on average, the contrast becomes weaker, the domain wall profiles do not change much with applied field. This frozen effect indicates that the wall position gets pinned. As we discussed earlier, structural inhomogeneities apparently play a significant role in our ultrathin films. The pinning at inhomogeneities induces a considerable fluctuation of the domain-wall width (δ_w) as one moves along the walls, which is clearly observed in Fig. 3(a) at zero field. When the field is increased, the fluctuations become smaller and eventually vanish. Meanwhile, δ_w shows a monotonic decrease with an increasing field. Line scans were taken perpendicular to the length of these regions and averaged along the length to improve statistics. A representative one is shown in Figs. 3(g) and 3(h). The box in 3(g) is the region over which the width was averaged and the length between the two red lines indicating δ_w is obtained by the trough-to-peak width of line scans in 3(h). Note that the scan profile is asymmetric, probably due to the structural imperfections.

Figure 4 shows δ_w obtained from the MFM line scans as a function of the applied field. We previously predicted[8] that $\delta_w \sim 1/H$, however, the agreement with the experiments was poor. We believe that the main reason is that the former result was derived by only considering the leading energy contributions, namely the Zeeman energy and the interlayer exchange energy. The exchange energy of the domain wall scales as $1/\delta_w$, so that small energy contributions, such as residual magnetocrystalline anisotropy and magnetostatic domain-wall interactions, become important for large δ_w. As the anisotropy reflects the density and strength of pinning sites, the fluctuations of δ_w at small fields should be stronger than those at large fields, consistent with what we observed

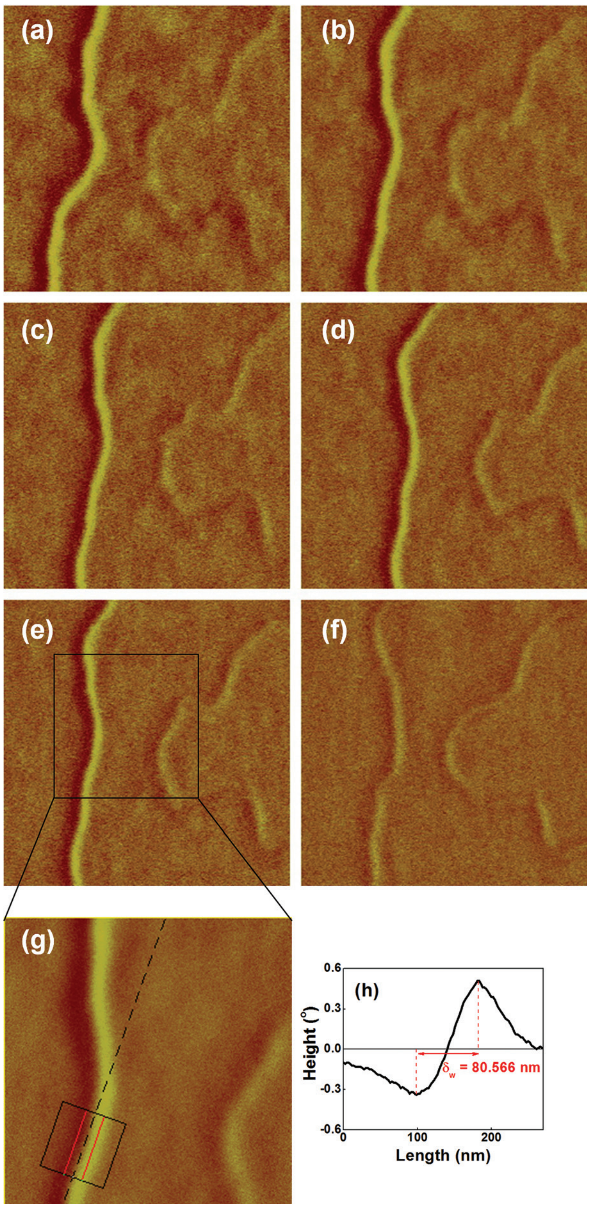

FIG. 3. (Color online) High resolution MFM images of the sample 5 nm Co/0.4 nm Ru/5 nm Co at room temperature with in-plane magnetic fields. (a)–(f) correspond to 0, 250, 500, 1000, 1250, 2000 Oe. Each image is 2.5×2.5 μm^2 in size. (g) Represents the region chosen from (e) with 1.25×1.25 μm^2 in size and (h) shows the line scans, averaged over the region enclosed in the box in (g). The y-axis indicates the MFM tip response.

in Fig. 3. To calculate the effect of the additional terms, we assume a Bloch-type domain-wall fine structure, and this yields the micromagnetic energy as a function of δ_w and magnetization m. The corresponding energy function is

$$E = 2t\left(\frac{4A}{\delta_w} + \frac{\mu_o}{2}M_sHm\delta_w + \mu_o m^2 M_s^2\frac{\delta_w t}{\delta_w + 2t} + K\delta_w\right). \quad (2)$$

A is the exchange stiffness of Co (about 20 pJ/m). The factor of 4 in the exchange term originates from the exchange expression $(\nabla \cdot \mathbf{m})^2$and means that m changes from $+1$ to -1 (or vice versa) over the distance δ_w. The second term is the Zeeman energy, the third term is the self interaction of the wall, derived from the demagnetizing factor $D = 2t/(\delta_w + 2t)$, shown as an inset in Fig. 4, and the last term is the magnetic anisotropy. For arbitrary fields, the domain-wall width is determined by minimizing Eq. (2) with respect to δ_w:

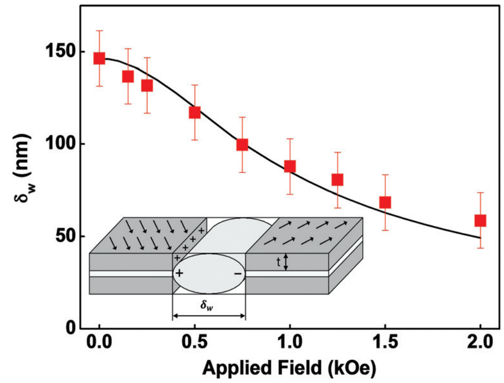

FIG. 4. (Color online) Domain-wall width as a function of applied magnetic field. Solid squares give the compiled line scan data from Fig. 3. The 15 nm error bars account for the MFM resolution. The solid line is the model calculation with $J = -2.1$ mJ/m^2. The inset shows the magnetostatic domain-wall interactions in the trilayer, The energy in the wall is estimated from the demagnetizing factor $D = R_z/(R_x+R_z) = 2t/(\delta_w+2t)$ of a long rod with an ellipsoidal cross section.

$$\delta_w = \sqrt{\frac{4A}{K + \frac{\mu_o}{2}M_sHm}}. \quad (3)$$

Here, $m = \frac{\mu_o M_s Ht}{2|J|}$ for small fields and $m = 1$ for large fields. The fitting curve is shown in Fig. 4 as a solid line by using $J = -2.1$ mJ/m^2 obtained from the dynamic calculations. Our micromagnetic model quantitatively provides a fairly good description of the experiments. Note that the value of K is approximately 3700 J/m^3, which is much smaller than the value for bulk Co, but this is consistent with observed low in-plane coercivity.

In summary, our dynamic measurements of Co/Ru/Co trilayers show that the strength of coupling is controlled by the interlayer thickness. The pump-probe technique yields two precessional frequencies which can be interpreted by a LLG based model. The semiquantitative agreement can be ascribed as the effect of structural inhomogeneities. Due to the pinning at inhomogeneities, MFM images show the frozen domain walls and a variation of δ_w. We calculated the fine structure of our films to provide a quantitative simulation of δ_w as a function of field.

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